

Can shadowing mimic the QCD phase transition?

L.V. Bravina,^{1,2} E.E. Zabrodin,^{1,2} Amand Faessler,¹ C. Fuchs¹

¹ *Institute for Theoretical Physics, University of Tübingen,
Auf der Morgenstelle 14, D-72076 Tübingen, Germany*

² *Institute for Nuclear Physics, Moscow State University, 119899 Moscow, Russia*

Abstract

The directed flow of protons is studied in the quark-gluon string model as a function of the impact parameter for S+S and Pb+Pb reactions at 160 AGeV/ c . A significant reduction of the directed flow in midrapidity range, which can lead to the development of the antiflow, is found due to the absorption of early emitted particles by massive spectators (shadowing effect). This effect can mimic the formation of the quark-gluon plasma (QGP). However, in the absorption scenario the antiflow is stronger for the system of light colliding nuclei than for the heavy ones, while in the case of the plasma creation the effect should be opposite.

PACS numbers: 25.75.-q, 25.75.Ld, 24.10.Lx

Typeset using REVTeX

The search for a phase transition from nuclear matter to the quark-gluon plasma (QGP) is one of the main goals of heavy ion collisions at ultrarelativistic energies. The creation of the QGP at temperatures well above the transition temperature $150 \text{ MeV} \leq T \leq 200 \text{ MeV}$ is expected at energies of heavy ion colliders, RHIC ($\sqrt{s} = 200 \text{ AGeV}$) and LHC ($\sqrt{s} = 5.5 \text{ ATeV}$). However, the possibility to reach the transition region of the mixed hadron-QGP phase at AGS ($E_{lab} = 10.7 \text{ AGeV}$) and SPS ($E_{lab} = 160 \text{ AGeV}$) energies is not ruled out.

The collective flow of particles produced in heavy ion collisions is one of the few signals which are extremely sensitive to the formation of a new state of matter (for review see, e.g., [1–3] and references therein), since the flow is connected to the equation of state (EOS) of the medium. The presence of the QGP undergoing a phase transition to hadronic matter results in a reduction of pressure [4,5] and, therefore, causes the so-called softening of the EOS [6,7] which can be detected experimentally. This inspires a great interest of both experimentalists and theoreticians for the phenomenon of the transverse (to the beam axis) collective flow. The transverse flow is conventionally subdivided into radial, directed and elliptic flow. The latter two are attributed only to noncentral collisions. Directed flow develops along the x -axis (impact parameter axis perpendicular to the beam axis) of the reaction plane. The subject of the present study is the directed flow of protons, which is most distinct and less affected by other effects [8]. The directed flow of protons is believed to have a characteristic S -shape of the mean transverse momentum $\langle p_x \rangle$ versus rapidity y in the reaction plane. Indeed, this behaviour was observed in experiments at BEVALAC/SIS energies ($E_{lab} = 100 \text{ AMeV} - 1 \text{ AGeV}$) [9–12], and at AGS and SPS energies [13–15]. However, the midrapidity region $|y_{c.m.}| \leq 0.4$ is usually not covered by the experimental apparatus.

Investigations of the directed flow at AGS energies with the quark-gluon string model (QGSM), made by one of the authors some time ago [16], revealed the appearance of the antiflow, caused by the shadowing effect, mainly in the midrapidity region. The antiflow is found to be most pronounced in semicentral and peripheral collisions of light nuclei. For heavy systems, like Au+Au, at 10.7 AGeV the effect seems to be quite small.

It is worth noting that the antiflow signal is not a feature attributed solely to the particular microscopic model such as QGSM. Strong antiflow of protons in the midrapidity range is predicted by the VENUS model for very peripheral ($b = 8 - 10 \text{ fm}$) Pb+Pb collisions at SPS energy [15]. The plateau in midrapidity region of the directed flow in semiperipheral ($b \leq 7 \text{ fm}$) Au+Au collisions at $E_{lab} = 25 \text{ AGeV}$ is found in the UrQMD calculations [17]. Studies of the nucleon directed flow in terms of the first Fourier coefficient [18], v_1 , of the particle azimuthal distribution, made recently within the RQMD model for semiperipheral and peripheral heavy ion collisions at energies from SPS to RHIC [19,20], also demonstrate the anisotropy indicated by deviations of v_1 from the straight line behaviour in the midrapidity region.

On the other hand, hydrodynamic simulations of heavy ion collisions with the QGP EOS indicate the creation of a similar antiflow in the midrapidity region [5,17,21,22]. No deviations from the straight line of the function $\langle p_x(y) \rangle$ in this range have been found in the simulations with a pure hadronic EOS. To get a clear signal of the plasma creation it is very important, therefore, to trace to what extent the development of the antiflow may be caused by any other processes not directly related to the formation of the QGP. We aim to study the dependence of the directed flow of protons on the impact parameter in the collisions of light and heavy ions at SPS energies.

For the simulations of nuclear interactions the microscopic quark-gluon string model with rescatterings [23] is employed. It treats the hadronic and nuclear interactions on the basis of the Gribov-Regge theory accomplished by the string phenomenology. As independent degrees of freedom the model includes octet and decuplet baryons, and octet and nonet vector and pseudoscalar mesons, as well as their antiparticles. For simplicity the fine tuning mechanisms such as mean fields, enhanced in-medium cross sections, colour coherent effects or string-string interactions are disregarded in the present version of the model. A formation of the QGP is also not assumed in the QGSM, although one can consider the appearance of non-particle objects, strings, as a precursor of the plasma creation. The model has successfully predicted the magnitude of the directed flow at SPS energies [4] far before its experimental discovery [14,15], and up to now it provides one of the best agreements with the experimental data [15] among the microscopic models.

For the simulations at 160 AGeV two symmetric nuclear systems, a light ($^{32}\text{S}+^{32}\text{S}$) and a heavy one ($^{208}\text{Pb} + ^{208}\text{Pb}$), have been chosen. The mean in-reaction plane transverse flow of protons as a function of rapidity is defined in the calculations as

$$\langle p_x(y)/A \rangle = p_x \frac{dN^p}{dy} \bigg/ \frac{dN^p}{dy} \equiv \langle (\vec{p}_T(y)/N^p, \vec{b}) / |\vec{b}| \rangle, \quad (1)$$

where N^p is the number of protons and b is the impact parameter.

To compare heavy ion systems with different radii, the distributions (1) are studied as a function of the reduced impact parameter, $\tilde{b} = b/b_{max}$. This parameter varies in the simulations from $\tilde{b} = 0.15$ (or even 0.05) for central collisions up to $\tilde{b} = 0.9$ corresponding to rather peripheral ones. For a symmetric system the maximum impact parameter is, apparently, $b_{max} = 2R_A$, that gives $b_{max} = 7.11$ (13.27) fm for S+S (Pb+Pb) collisions.

Results are shown in Figs. 1(a) and 1(b). Here the in-plane transverse momentum of protons is defined in the scale-invariant form [24] $\langle \tilde{p}_x(\tilde{y})/A \rangle$, where the reduced momentum, $\tilde{p}_x = p_x/p_{c.m.}$, and reduced rapidity, $\tilde{y} = y/y_{c.m.}$, are normalized to the center-of-mass momentum and rapidity of the projectile, $p_{c.m.} = 8.65$ and $y_{c.m.} = 2.9$, respectively. Immediately one can see that for the light system [Fig. 1(a)] the flow has a more complex structure in the midrapidity region compared to a simple linear dependence shown by a solid line in Fig. 1. The antiflow in the central rapidity region $|y| \leq 1$ develops already at $\tilde{b} \leq 0.3$. Towards the semicentral and peripheral collisions the zone of irregularities in the behaviour of the directed flow becomes broader. In the case of heavy nuclei [Fig. 1(b)] the disappearance of the flow occurs also at $\tilde{b} = 0.3$ but within the narrower region, $|y| \leq 0.25$. The distinct antiflow signal seems to appear only in peripheral, $\tilde{b} \geq 0.75$, collisions. As expected, the flow signal at an SPS energy is significantly weaker compared to that in calculations at an AGS energy [16].

To quantify the strength of the antiflow and normal flow separately the reaction zone was subdivided into rectangular cells with volumes $V^{cell} = 1.6 \times 1.6 \times 1.2 = 3 \text{ fm}^3$. The time evolution of the baryon density, n_B , and the collective velocity of the cells, \vec{v}_{cell} , was considered. To distinguish between the normal flow and antiflow components the step function, Θ , of the product $p_x^{cell} y^{cell}$ is used in the calculations:

$$\Theta_{flow} = \begin{cases} 1, & \text{if } p_x^{cell} y^{cell} > 0 \\ 0, & \text{otherwise;} \end{cases}$$

$$\Theta_{a.-flow} = \begin{cases} 1, & \text{if } p_x^{cell} y^{cell} < 0 \\ 0, & \text{otherwise} . \end{cases}$$

Figure 2 depicts a snapshot of baryon densities and collective velocities of the cells in S+S collisions at SPS energy, calculated at fixed impact parameter $b = 2.13$ fm ($\tilde{b} = 0.3$) at time $t = 6$ fm/c. The antiflow component develops towards the relatively more dilute zones of nuclear collisions, whereas the normal flow component follows the baryon rich remnants of the interacting nuclei. Apparently, the total flow is determined by the interplay between these two components. This leads to the reduction of the total flow because of their mutual cancellation.

To calculate the mean directed flow of protons in the forward or backward hemisphere of the center-of-mass system, $\langle p_x^{dir}/N^p \rangle$, the proton rapidity distribution, dN^p/dy , should be integrated over the whole rapidity range with the weight $\langle p_x(y)/N^p \rangle$, given by Eq. (1), namely,

$$\left\langle \frac{p_x^{dir}(y)}{N^p} \right\rangle = \int \text{sign}(y) \frac{dN^p}{dy} \left\langle \frac{p_x(y)}{A} \right\rangle dy \bigg/ \int \frac{dN^p}{dy} dy . \quad (2)$$

The time evolution of the proton directed flow in forward hemisphere is shown in Fig. 3. We see that both, the normal flow component and the antiflow component, develop quickly and reach a maximum at $t \cong 2$ fm/c after the beginning of collision. The partial flows are almost two orders of magnitude larger than the resulting directed flow. It is worth noting also that the total directed flow of protons decreases slightly after $t = 6$ fm/c. This is due to decays of baryonic resonances, which dominate over the formation of resonances at the late stage of the reaction. Despite the normal flow component, integrated over the whole rapidity range, is always slightly larger than the antiflow one, in some rapidity windows the antiflow component can overshadow its normal counterpart. For instance, particles emitted with small rapidities at the early stage of the reaction in “normal” direction are absorbed by two massive spectators, while particles emitted in the opposite direction remain unaffected. The signal becomes weaker with increasing centrality of the collision because of the shrinking of space where the particles could be emitted unscreened. In heavy systems the emission of particles from the central fireball increases. Thus the absorption of several early emitted particles by the flying spectators becomes less effective, and the relative strength of the antiflow decreases.

Figure 4 presents the rapidity distribution of the directed flow of protons together with the flow and antiflow components at the late stage of S+S collisions with $\tilde{b} = 0.3$. The resulting flow has a characteristic wavy structure. It tends generally to grow with rapidity rising from $y = -2.5$ to $y = -0.4$, and from $y = 0.4$ to $y = 2.5$. In the midrapidity range $|y| \leq 0.4$ the total flow decreases. This effect can imitate the expected softness of the EOS due to the plasma creation and, therefore, it should be taken into account in the analysis of experimental data.

In conclusion, directed flow of protons is studied in semicentral and peripheral sulphur-sulphur and lead-lead collisions at 160 AGeV generated by a quark-gluon string model of nuclear collisions. The flow is shown to have a complex structure in the rapidity range $|y| \leq 1.5$, which is strongly dependent on the centrality of the collision, as well as on the mass number of colliding nuclei. The total directed flow can be decomposed onto the normal

component, which follows the outgoing residues of collided ions, and the antiflow component, which develops in the opposite direction, where the baryon matter is more dilute.

Although these partial components are relatively large, their mutual cancellation leads to a rather modest signal of the total flow. In S+S collisions with an impact parameter $b \cong 2$ fm ($\tilde{b} \cong 0.3$) the antiflow already dominates over the normal flow in the central rapidity range $|y| \leq 0.4$. This circumstance causes the decrease of the total flow. In heavy systems like Pb+Pb the effect is most pronounced in peripheral collisions with $b \cong 9$ fm ($\tilde{b} \cong 0.7$) or larger, although the significant disappearance of the flow in the range $|y| \geq 0.5$ takes place already in semicentral events with $b = 4$ fm ($\tilde{b} = 0.3$). This can be misinterpreted as an indication for the softening of the EOS of strongly interacting matter.

Note that in the microscopic string model like QGSM the total directed flow of protons changes its behaviour in the central rapidity region because of almost purely geometrical reasons. Therefore, the effect is more distinct in the collisions of light ions. With the rise of incident energy the remnants of nuclei move faster thus giving space for the antiflow development. Hence, the characteristic change of sign of the total flow in heavy ion collisions should appear not only in peripheral collisions, but also in semicentral and even in almost central collisions ($1 \text{ fm} \leq b \leq 3 \text{ fm}$) at RHIC energies ($\sqrt{s} = 200 \text{ AGeV}$).

This description is opposite to the picture of non-central heavy ion collisions given by hydrodynamic models. In hydrodynamics the creation of a QGP is likely to occur in heavy (Pb+Pb or Au+Au) systems rather than in light (S+S) systems. The formation even of a small amount of plasma with the subsequent phase transition to the hadron phase can also produce the negative slope of the $\langle p_x(y) \rangle$ -distribution in the midrapidity region. The effect, therefore, should essentially be more pronounced in heavy ion collisions compared to collisions of light ions with the same reduced impact parameter. The situation clearly awaits better experimental data on proton directed flow in the central rapidity region.

Acknowledgments. We acknowledge fruitful discussions with L. Csernai, M. Gyulassy, E. Shuryak, H. Sorge, H. Stöcker, and Nu Xu. This work was supported in part by the Bundesministerium für Bildung und Forschung (BMBF) under contract 06TÜ887.

REFERENCES

- [1] H. Stöcker and W. Greiner, Phys. Rep. 137 (1986) 277.
- [2] W. Reisdorf and H.G. Ritter, Annu. Rev. Nucl. Part. Sci. 47 (1997) 663.
- [3] J.-Y. Ollitrault, Nucl. Phys. A 638 (1998) 195c; Phys. Rev. D 46 (1992) 229.
- [4] N.S. Amelin et al., Phys. Rev. Lett. 67 (1991) 1523.
- [5] L.V. Bravina, L.P. Csernai, P. Lévai, D. Strottman, Phys. Rev. C 50 (1994) 2161;
L.V. Bravina et al., Nucl. Phys. A 566 (1994) 461c.
- [6] C.M. Hung and E.V. Shuryak, Phys. Rev. Lett 75 (1995) 4003.
- [7] D.H. Rischke and M. Gyulassy, Nucl. Phys. A 597 (1996) 701.
- [8] S.A. Voloshin, Phys. Rev. C 55 (1997) R1630.
- [9] H.-Å. Gustafsson et al., Phys. Rev. Lett. **52** (1984) 1590.
- [10] R.E. Renfordt et al., Phys. Rev. Lett. **53** (1984) 763.
- [11] V. Ramillien et al., Nucl. Phys. A 587 (1995) 802.
- [12] Y. Leifels et al., Phys. Rev. Lett. **71** (1993) 963.
- [13] J. Barrette et al., Phys. Rev. Lett. **73** (1994) 2532; Phys. Rev. C **59** (1999) 884.
- [14] H. Appelshäuser et al., Phys. Rev. Lett. **80** (1998) 4136.
- [15] M.M. Aggarwal et al., Phys. Rev. Lett. (submitted) (nucl-ex/9807004v2).
- [16] L.V. Bravina, Phys. Lett. B 344 (1995) 49.
- [17] J. Brachmann et al., nucl-th/9908010.
- [18] A.M. Poskanzer and S.A. Voloshin, Phys. Rev. C 58 (1998) 1671.
- [19] H. Liu, S. Panitkin, and N. Xu, Phys. Rev. C 59 (1999) 348.
- [20] R.J.M. Snellings et al., nucl-ex/9908001.
- [21] J. Brachmann et al., Nucl. Phys. A 619 (1997) 391.
- [22] L.P. Csernai and D. Röhrich, Phys. Lett. B 458 (1999) 454.
- [23] N.S. Amelin et al., Sov. J. Nucl. Phys. 52 (1990) 172; Phys. Rev. C 47 (1993) 2299.
- [24] L.P. Csernai, Introduction to Relativistic Heavy Ion Collisions (Wiley, New York, 1994).

FIGURES

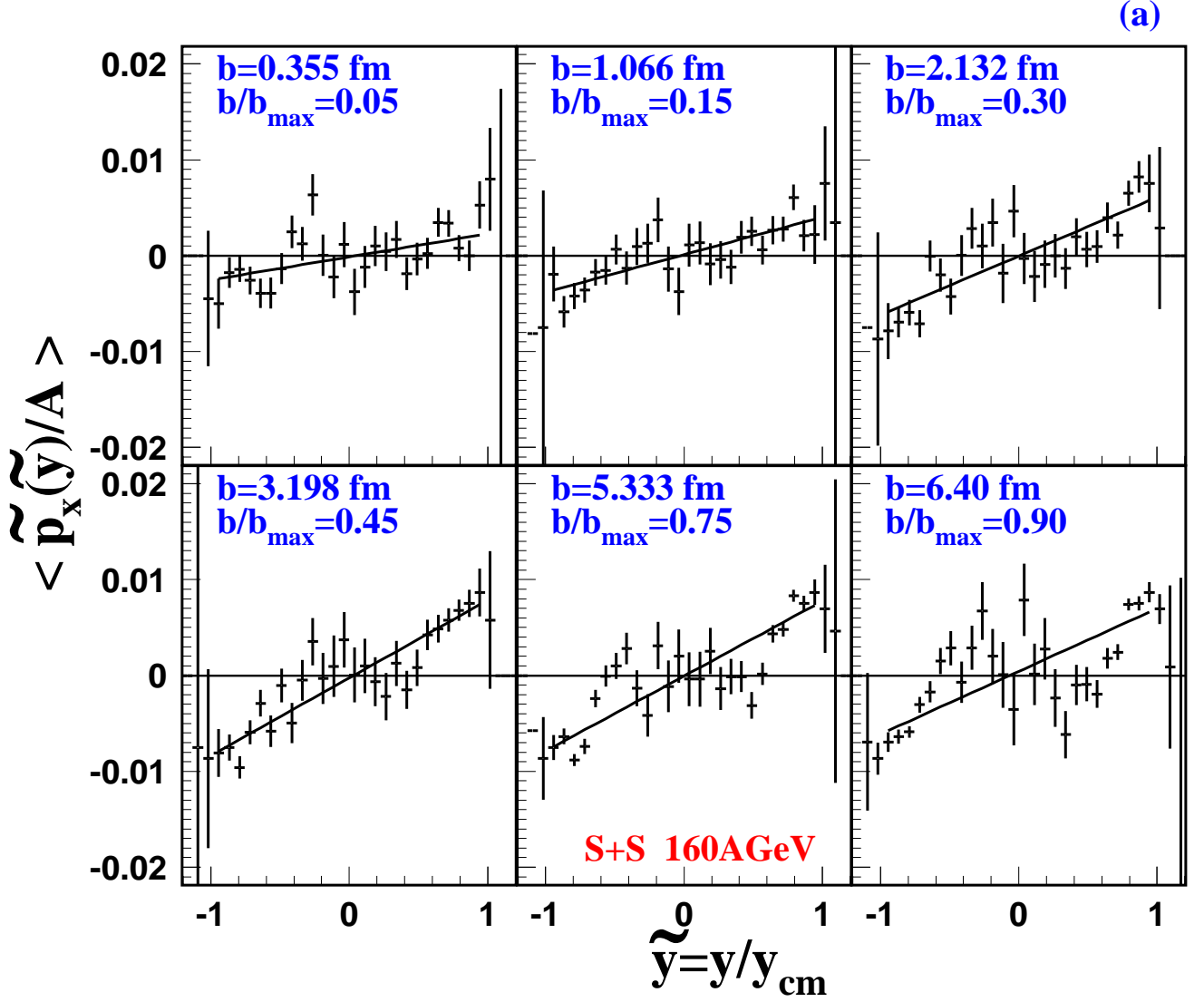
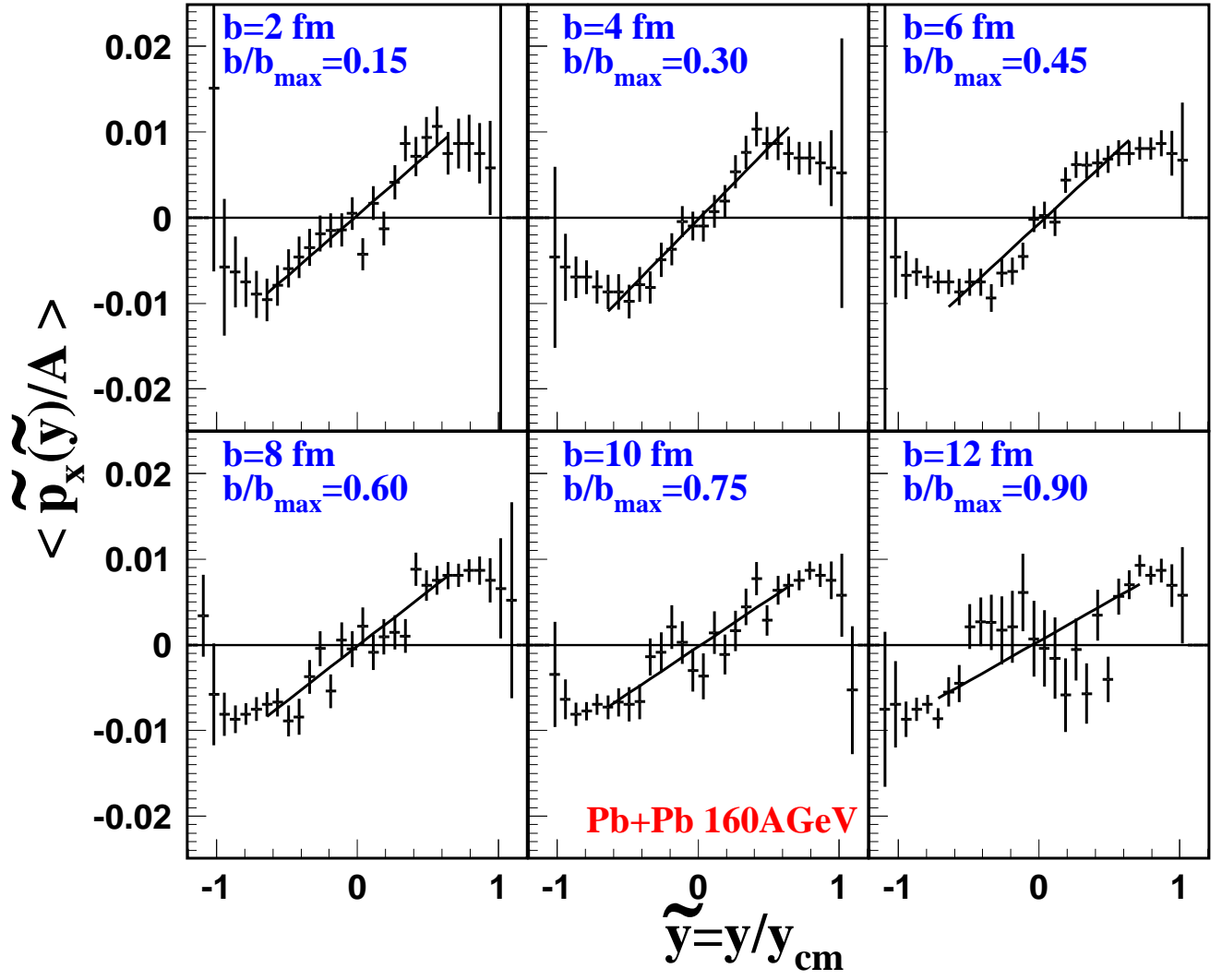


FIG. 1. Directed flow of protons, $\langle \tilde{p}_x(\tilde{y})/A \rangle$, as a function of rapidity, y , calculated in QGSM for $^{32}\text{S}+^{32}\text{S}$ (a) and $^{208}\text{Pb}+^{208}\text{Pb}$ (b) calculations at 160 AGeV. Values of the impact parameter, b , and the reduced impact parameter, $\tilde{b} = b/b_{max}$, are listed in each panel of the figure. Results of the simulations are fitted to linear dependence (solid line) in rapidity interval $|\tilde{y}| \leq 1$.

(b)



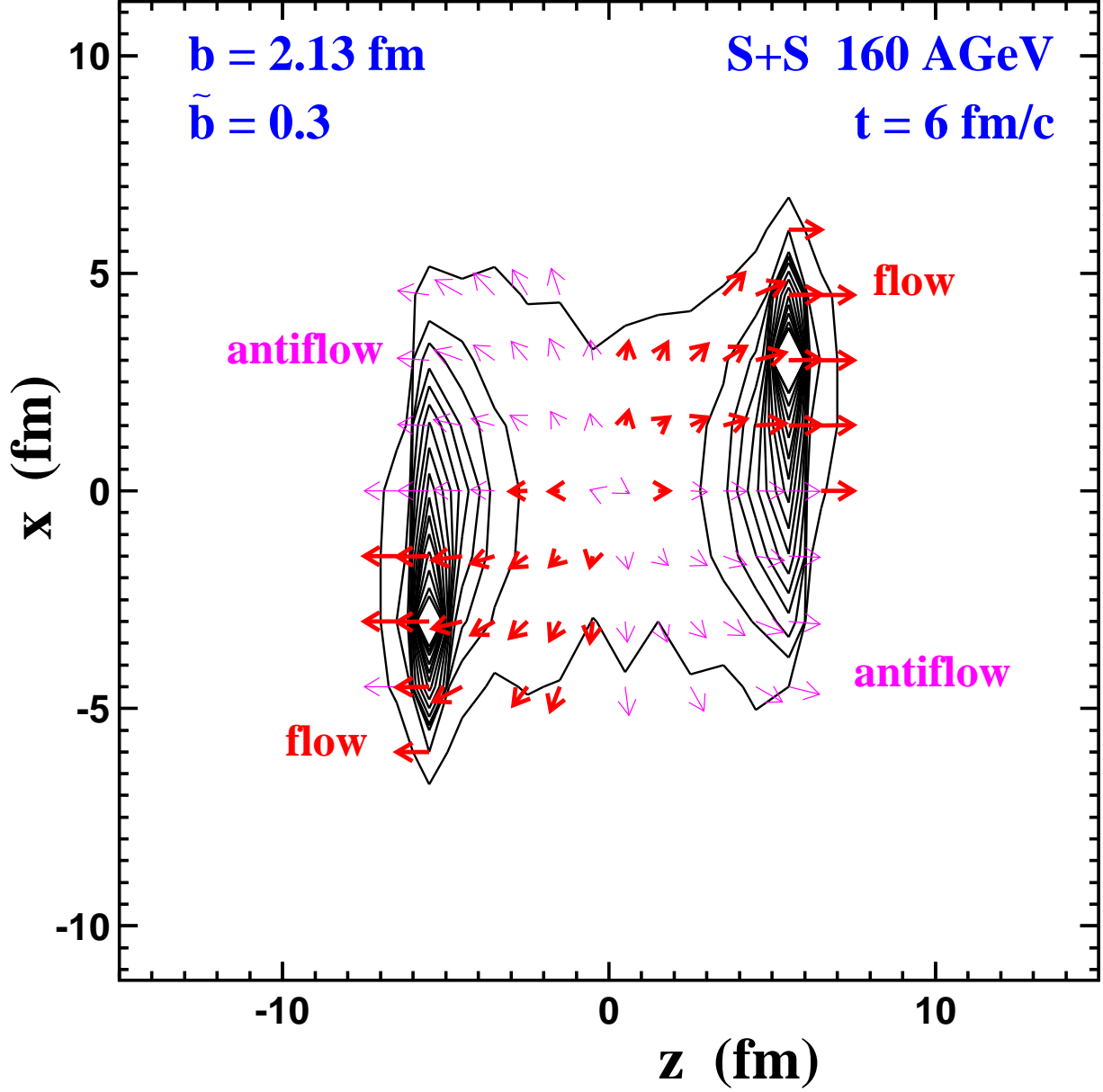


FIG. 2. Space-time evolution of the baryon density, n_B/n_0 (contour plots), and collective velocity, \vec{v} (arrows), of the cells with volume $V = 3 \text{ fm}^3$ each. Calculations are made in QGSM for semicentral ($b = 2.13$ fm) S+S collisions at SPS energy for all formed baryons at time $t = 6 \text{ fm}/c$. Contour plots correspond to $n_B/n_0 = 0.05, 0.25, 0.5, \text{ etc.}$ of normal baryon density.

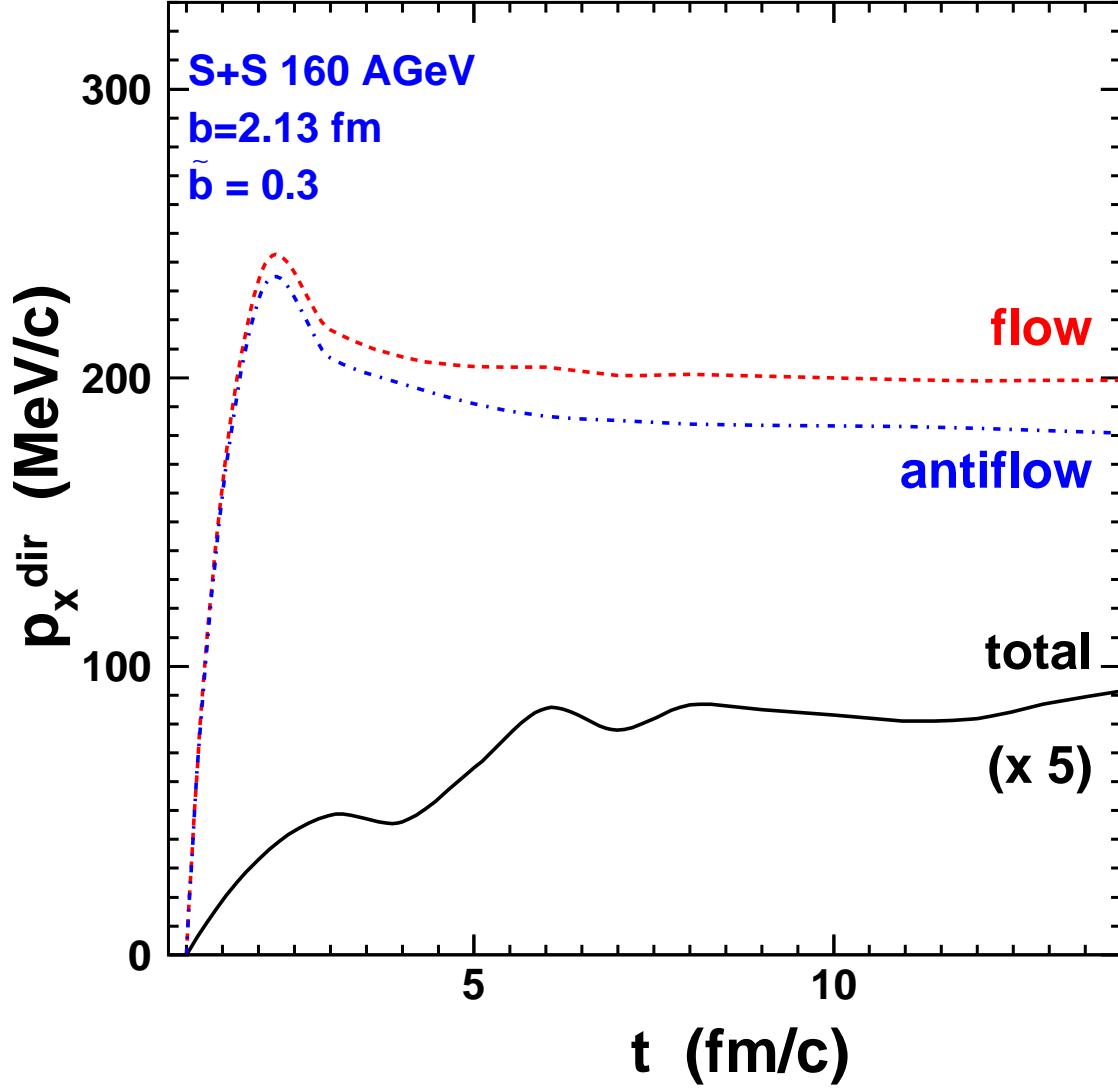


FIG. 3. Time evolution of the mean directed flow of protons in S+S collisions with the reduced impact parameter $\tilde{b} = 0.3$ at 160 AGeV/c. Dashed and dash-dotted curves indicate the normal and antiflow components, respectively. Full curve denotes the resulting flow multiplied by factor 5.

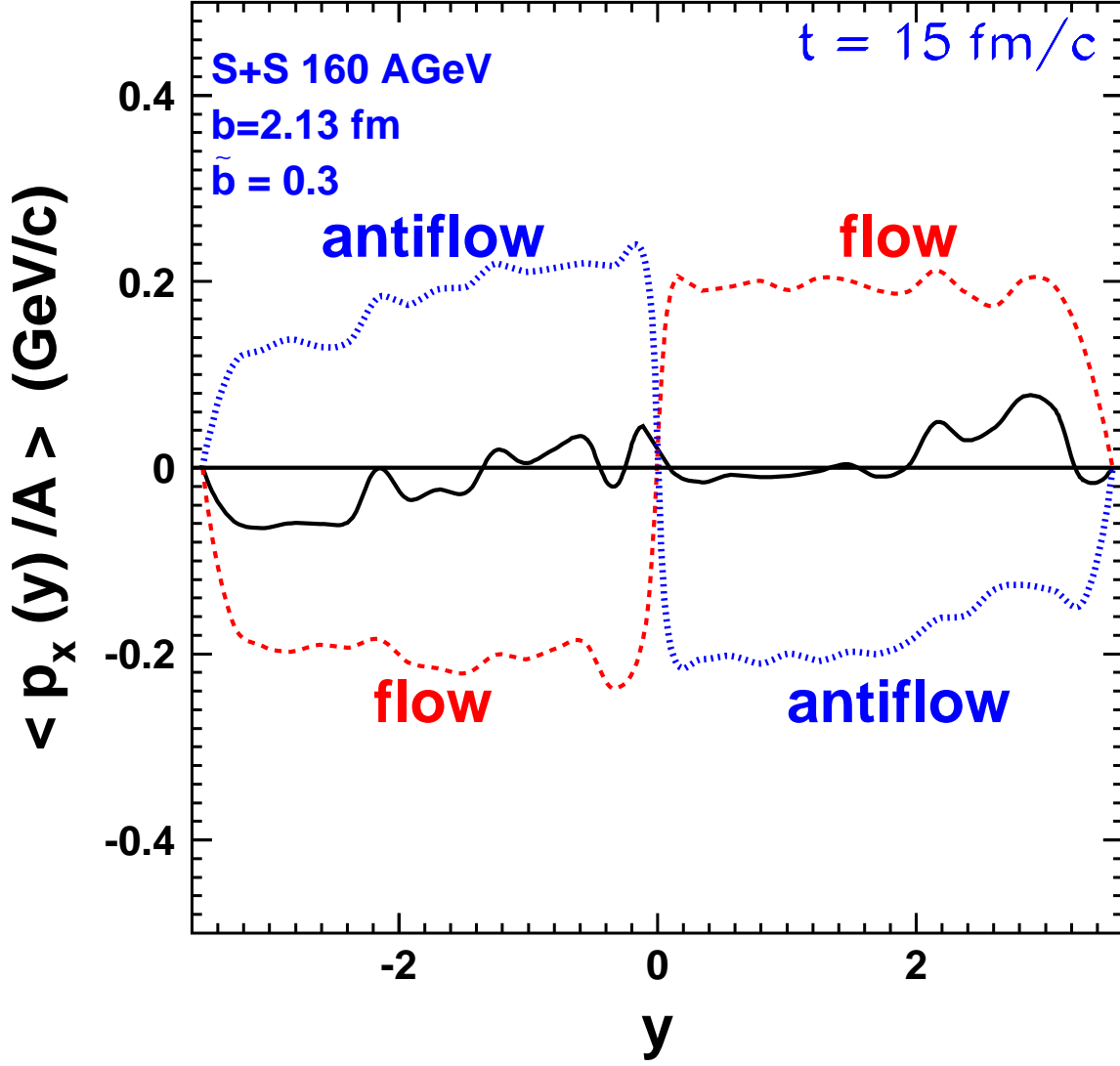


FIG. 4. Rapidity distribution of the directed flow of protons at $t = 15$ fm/c in S+S collisions with $\tilde{b} = 0.3$ at SPS energy. Dashed, dotted, and full curves indicate the normal and antiflow components, and the resulting flow, respectively.